# Adding a cusp magnetic field to the EQ-10 Z-pinch metrology source

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**ABSTRACT**

In the EQ10 Electrode-less Z-pinch metrology source[1] , the plasma length is controlled (in part) by bore geometry, which is subject to rigorous mechanical constraints. If the plasma length were reduced without reducing the total source power, the source usable brightness would increase. To do this we have introduced a cusp magnetic field into the Z-pinch region. The objective is to add an additional (non-plasma) source of axially-dependent pressure, which can be tailored to inhibit the radial collapse except in the center of the bore. While the incorporation of (approximately) uniform axial field in an EUV-producing Z-pinch has been studied previously[2], to our knowledge this is the first attempt to use a cusp field for this purpose. A preliminary design based on a hexapole cusp was executed. We will present the theoretical basis for this concept as well as some results, and anticipate useful discussion to elucidate the physics behind the (unexpected) behavior of the device.

[1] S. F. Horne, M. M. Besen, D. K. Smith, P. A. Blackborow, and R. D'Agostino, "Application of a high-brightness electrodeless Z-pinch EUV source for metrology, inspection, and resist development," Proc. SPIE, 6151, 201-210 (2006).

[2] Katsuki, Sunao, Akihiro Kimura, Yoshihiro Kondo, Hiroyuki Horita, Takao Namihira, Takashi Sakugawa, and Hidenori Akiyama. "Effects of an axial magnetic field on Z-pinch plasmas for extreme ultraviolet sources." Journal of applied physics 99, no. 1 (2006): 013305.

## Standard Z-pinch has electrodes –

**Forces plasma to have a specific maximum length – can't be longer than distance between electrodes, because current flows only there**

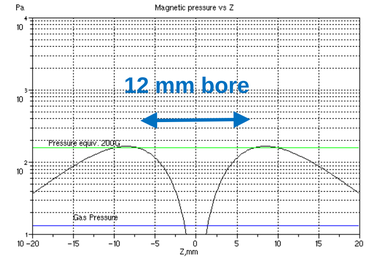
**A small (short) EUV emission region simplifies optics design, saves wasted light/power…**

**Electrode-less pinch has current flow over long region. How to control plasma length?**

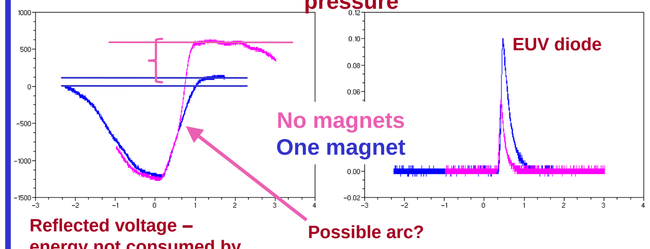
## Magnetic pressure profiles

**Three magnets in 6 positions produces ~ 10X neutral gas pressure at +/- 8 mm**

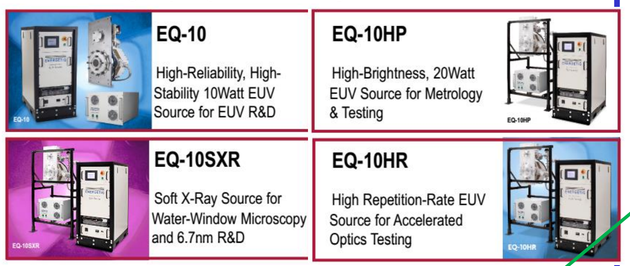
**Should be plenty of field to see any effect.**



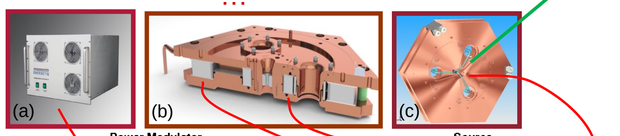

## Magnetic field allows more efficient operation at low pressure

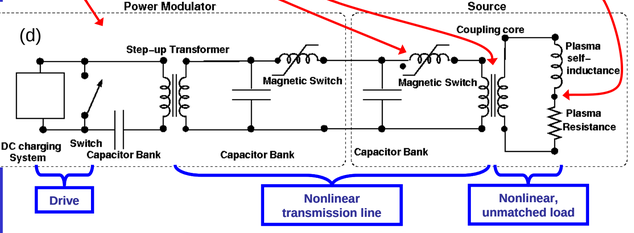



## *Energetiq EQ-10 – a family of EUV sources…*



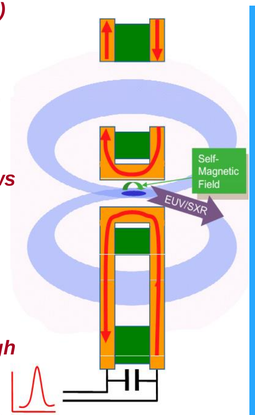

## *…based on a new concept - the Electrodeless Z-Pinch™*

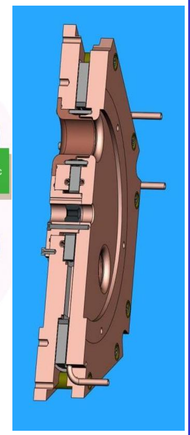



## *Operating principle..*

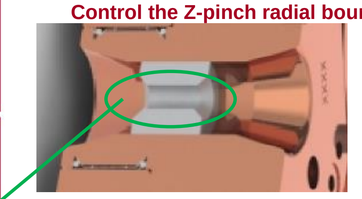
***Source is (electrically) two copper plates joined by conductive tube…***
***Voltage pulse applied to capacitor bank; current held off by magnetic switch allows capacitors to charge***
***Switch saturates; capacitor voltage appears across inner induction core…***
***Induces voltage in plasma region, through holes pierced in disks…***
***Current pulse flows in plasma, producing Z-pinch***



## Our approach..

**Control the Z-pinch radial boundary condition.**



**Time to pinch ~ initial plasma radius.**
**Once pinch occurs locally, plasma inductance increases locally; entire loop voltage drops across pinch.**
**Plasma length ~ bore length.**

**Challenge: Make the z-pinched plasma shorter than the bore.**

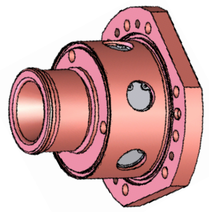
## An axial magnetic field B should inhibit the pinch – adds magnetic pressure. The collapsing pinch must compress the B-field as well as the plasma.

**Arrange for the field to be zero at the center of the bore**

$$P_m = B^2/(2\mu_0)$$

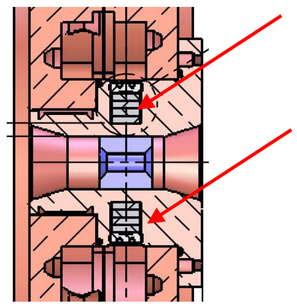
## How much B field? Three estimates:

**The uncompressed gas pressure:**
**P ~ 13 Pa; → B ~ 60 G**
**The compressed plasma pressure**
**P ~ 4.e6 Pa; → B ~ 3 T compressed**
**100 G uncompressed**
**The plasma self-field – B ~ 5T compressed; ~100-200 G uncompressed**



**Six magnet assemblies; similar poles inward facing creates a modified spindle cusp.**

**No space or access for coils… use permanent magnets**



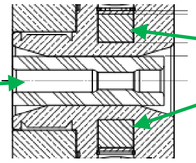
## First attempt… 3 x 6 magnets

**Complete failure.**
**Source would not operate.**
**Analysis… Magnets somehow caused plasma-bore arcing.**
**(Removing the magnets restored normal operation.)**
**Concept was abandoned for the moment.**

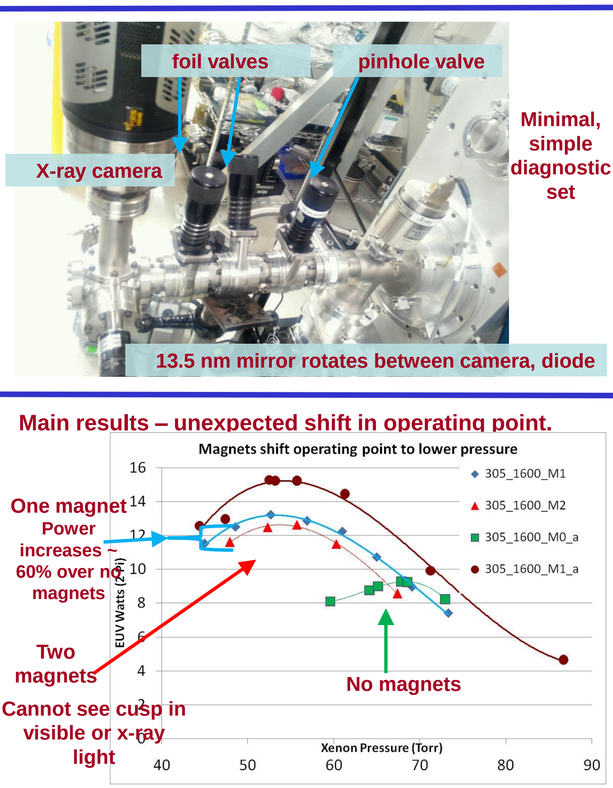
## Second attempt –full length SiC bore

**Shield the copper from the plasma.. .**

**Full length silicon carbide insert**

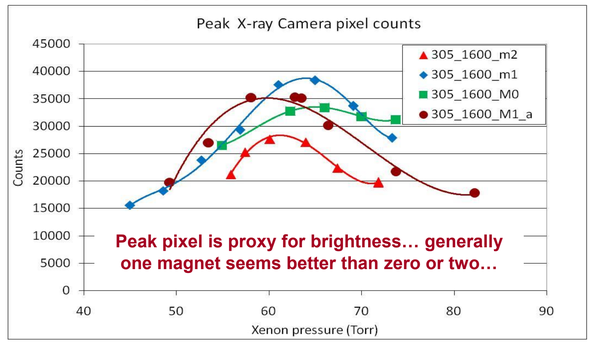


**Start with two magnets, not three**




**Minimal, simple diagnostic set**

## Brightness data shows weaker effect




## Conclusions

**The cusp field was supposed to shorten the plasma.**
**No effect was seen**
**Power, brightness data agree one magnet is better than zero or two**
**Main effect – seen – shift to lower pressure operating point**

## Possible explanation –E II B?

**Electric field E – Curl E ~ dB/dt in induction core**

**Magnetic field B – Curl B ~ J; J looks like a surface current on the same core, since core homogenizes fields due to magnets**

**Geometry of B,E fields should be very similar.**

**Could provide very efficient electron confinement, leading to higher electrical efficiency pinch.**

## Main results – unexpected shift in operating point.

**One magnet Power increases ~ 60% over no magnets**

**Two magnets**

**Cannot see cusp in visible or x-ray light**




## References and bibliography

- Blackborow, Paul A.; Gustafson, Deborah S.; Smith, Donald K.; Besen, Matthew M.; Horne, Stephen F.; D'Agostino, Robert J.; Minami, Youichi; Denbeaux, Gregory; "Application of the Energetiq EQ-10 electrodeless Z-Pinch EUV light source in outgassing and exposure of EUV photoresist" in Emerging Lithographic Technologies XI. Edited by Lercel, Michael J.. Proceedings of the SPIE, Volume 6517, pp. 65171W (2007).
- Sunao Katsuki, Akihiro Kimura, Yoshihiro Kondo, Hiroyuki Horita, Takao Namihira et al.," Effects of an axial magnetic field on Z-pinch plasmas for extreme ultraviolet sources", J. Appl. Phys. 99, 013305 (2006)
- M G Haines, "A Review of the Dense Z-pinch", Plasma Phys. Control. Fusion 53 (2011) 093001
- Paul A. Blackborow ; Matthew J. Partlow ; Stephen F. Horne ; Matthew M. Besen ; Donald K. Smith, et al. "EUV source development for AIMS and blank inspection", Proc. SPIE 7636, Extreme Ultraviolet (EUV) Lithography, 763609 (March 17, 2010);